DOCUMENT RESUME

ED 447 001 SE 064 306

AUTHOR	Hoernschemeyer, Don
TITLE	Invigorating Education with the Scientific Paradigm. Fastback 472.
INSTITUTION	Phi Delta Kappa Educational Foundation, Bloomington, IN.
ISBN	ISBN-0-87367-672-6
PUB DATE	2000-00-00
NOTE	43p.
AVAILABLE FROM	Phi Delta Kappa International, 408 N. Union, P.O. Box 789, Bloomington, IN 47402-0789.
PUB TYPE	Guides - Non-Classroom (055)
EDRS PRICE	EDRS Price MF01 Plus Postage. PC Not Available from EDRS.
DESCRIPTORS	*Science Process Skills; *Scientific Methodology; Scientific Principles; Secondary Education; *Teaching Methods; *Thinking Skills

ABSTRACT

This document supports the integration of the scientific method not only into science teaching but also into the entire curriculum. It argues that the methods and attitudes that have made science the most productive enterprise of the past 300 years can be adapted to most areas of secondary education. The scientist's way of thinking is described, particularly curiosity, creativity, objectivity, skepticism, and open-mindedness. Scientific methods including investigation and measurement, analysis and understanding are also discussed. It is concluded that the mental skills of science will be valuable for everyone who must deal successfully with life's challenges. (ASK)

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Invigorating Education with the Scientific Paradigm

Don Hoernschemeyer

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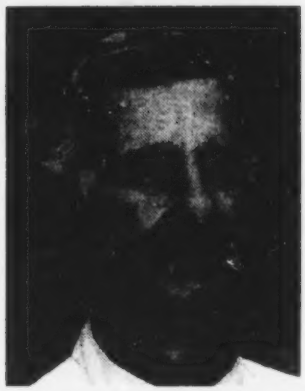

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Invigorating Education with the Scientific Paradigm

by
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ISBN 0-87367-672-6
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Bloomington, Indiana

Table of Contents

Introduction 7

Science and Other Areas of the Curriculum 10

The Scientist's Way of Thinking 16
- Curiosity 16
- Creativity 18
- Objectivity 21
- Skepticism 22
- Open-Mindedness 24

Scientific Methods 27
- Investigation and Measurement 27
- Analysis 30
- Understanding 32

Conclusion 38

References 40

Introduction

Teachers have an immense challenge. Not only must they teach the content of their subject, they also must help students learn *how* to think. Education for the 21st century demands knowing how to acquire and use information, how to think critically, how to critique our own reasoning, and how to understand complex issues. In addition, teachers must prepare their students for new, demanding state and national assessment standards.

Good teachers constantly look for ways to increase the effectiveness of their teaching and to help their students enjoy learning. They look for that emotional key that motivates a student to learn.

The scientific method can help teachers meet all of these challenges.

Are young scientists turned on? You bet they are! They are turned on by their instinctive curiosity, by a sense of wonder at the marvels of nature, by fascination with mysterious things, by direct interaction with objects of interest, and by emotional satisfaction when understanding occurs. And the thinking skills engendered by the scientific method are those we try to teach in programs on critical thinking.

This fastback is *not* about teaching science, but about teaching all subjects. It is about integrating the scientific method into the entire curriculum. The methods and attitudes that have made science the most productive enterprise of the past three hundred years can be adapted to most areas of secondary education.

In *The Power of Their Ideas*, Deborah Meier describes the major intellectual habits that should be internalized by all students and used no matter what they are studying:

- Being keenly observant.
- Imagining and wondering.
- Being both skeptical and open-minded.
- Recognizing the importance of good evidence.
- Being able to communicate what one has learned.
- Considering the quality of evidence.
- Weighing confidence in the source of information.
- Making cause-and-effect connections.
- Hypothesizing about possible explanations.
- Considering the importance of the intellectual work.

Meier writes: "Lawyers tell us these habits are very lawyerly, but journalists and scientists tell us they are basic to what they do as well. As a historian, I recognize them as being at the heart of my field" (1995, p. 41).

The award-winning science teacher, Anne Buchanan, directly related science to the thinking habits and skills described by Deborah Meier. In an article on the Access Excellence website of the National Health Museum, Buchanan wrote:

> Critical thinking is disciplined, self-directed thinking. It requires thinking about your thinking while you are thinking in order to make your thinking clearer, more accurate and more defensible. Indeed, scientists do this already every time they use the scientific method. They ask questions, gather and assess relevant information, come to well-reasoned conclusions/solutions, and they communicate effectively when they write up results. The traits of a good scientist *are* the traits of a well-cultivated critical thinker.

The thinking skills developed in science are useful in other disciplines. The truth of this assertion follows from the fact that scientific thought is only a form of rational thinking shaped to special requirements for discovering new knowledge. Anyone can use the kind of critical thinking employed so successfully in science.

Science and Other Areas of the Curriculum

Science is a discipline with the twin goals of discovering the essence of the natural world and understanding how it works. Scientists carry out investigations by using special methods. They rigorously analyze their observations. They synthesize those observations into a coherent understanding; and they report their results to their peers. The accuracy and fidelity of results to the real world are maintained by an attitude of objectivity. Consensus on truth about reality is fostered by intense dialogue and an openness to opposing ideas.

Scientists often emphasize skepticism and the willingness to abandon ideas that are not supported by evidence. Carl Sagan, the astrophysicist and author of many popular books on science, wrote:

> Science is different from many another human enterprise. . . in its passion for framing testable hypotheses, in its search for definitive experiments that confirm or deny ideas, in the vigor of its substantive debate, and in its willingness to abandon ideas that have been found wanting. If we were not aware of our own limitations, though, if we were not seeking further data, if we were

> unwilling to perform controlled experiments, if we did not respect the evidence, we would have very little leverage in our quest for the truth. (1996, p. 263)

The Nobel Prize-winning physicist Richard Feynman described science this way:

> Science is a way to teach how something gets to be known, what is not known, to what extent things are known (for nothing is known absolutely), how to handle doubt and uncertainty, what the rules of evidence are, how to think about things so that judgments can be made, how to distinguish truth from fraud and show. (in Gleick 1992, p. 285)

The most prominent features of the scientific paradigm are:

1. There is a quest to discover how things work. There is a habit of asking probing questions, especially about incongruous facts. There are no sacred truths or forbidden questions. Ignorance is acknowledged and room is left for doubt.
2. Complex subjects are divided into simpler parts for independent study. When they are understood separately, the knowledge is synthesized to give a description of the whole.
3. Whenever possible, analyses are quantitative. Symbols, figures, mathematics, and incisive language are used to describe the work. Thinking is guided by, but not limited by, current theories and principles.
4. Theoretical and experimental work are complementary activities. Exploratory experiments dis-

close new information, and challenge experiments test theories. Validated theories guide the planning of experimental work.

5. To investigate nature, discriminating measurements or observations are made under controlled or documented conditions. Experiments are designed to answer carefully framed questions. Investigators are especially attentive to unexpected results.
6. Explanations for incongruous facts and puzzling phenomena are sought by forming testable hypotheses, then devising and running experiments to judge their validity.
7. Theoretical models are created to explain a new phenomenon or a larger set of phenomena. Imagination, intuition, analytical thinking, and aesthetics guide the work. Validated theories are used to deepen understanding and make predictions.
8. All principles and theories must be consistent with each other. None are considered permanent or above challenge. Issues are investigated in depth until contradictions and ambiguities are resolved.
9. Results of experimental and theoretical studies are published in scientific journals. There are forums where new ideas and experimental results are discussed and challenged. Peer review is an established tradition.
10. There is continual learning, including exposure to ideas and practices in different disciplines. Scientific literature is studied; new techniques are

learned; expertise is maintained. Mentoring is a universal practice.

11. New theories and experimental results are considered tentative until thoroughly corroborated. New data and ideas become established facts, laws, and theories only after there is consensus among scientists with expertise in the subject.

Obviously, the scientific method is applicable to teaching and learning science. Perhaps less obvious is that it also is applicable to teaching and learning mathematics, which has its unique requirements for proving theorems, deducing the consequences of theorems, and applying theorems to problems. Nevertheless, the logical thinking skills cultivated in science are equally valuable in the learning of mathematics, and vice versa, because both employ precise definitions of concepts, use deductive and inductive reasoning, and use functional representations of concepts.

The scientific way of thinking also can contribute to students' learning and achievement throughout the curriculum. In particular, this fastback will examine how the scientific paradigm relates to the language arts and history/social studies areas of the curriculum.

The *Frameworks for California Public Schools* (1987, 1997) propose that critical thinking skills be included at every grade level. Standards for the history and social science curriculum include:

1. There is an emphasis on the study of major historical events and periods in depth, as opposed to superficial skimming.

2. Teachers present controversial issues honestly and accurately within their historical or contemporary context. Through the study of controversial issues, students should learn that judgments should be based on reasonable evidence and not on bias and emotion.
3. Critical thinking requires a questioning mind and a skeptical withholding of assent about the truth of a statement until it can be critically evaluated.
4. The most basic study skills of the history-social science fields involve obtaining information and judging its value, reaching reasoned conclusions based on evidence, and developing sound judgment.
5. Students develop the ability to: a) formulate appropriate questions leading to a deeper and clearer understanding of an issue; b) distinguish among facts, opinion, and reasoned judgment; c) identify unstated assumptions; d) test conclusions or hypotheses; e) predict probable consequences of an event; and f) understand and distinguish cause, effect, sequence, and correlation.
6. The framework supports the frequent study and discussion of the fundamental principles embedded in the U.S. Constitution and Bill of Rights.

Standards for the language arts curriculum include:

1. Ask and evaluate questions, and develop ideas leading to inquiry, investigation, and research.
2. Verify and clarify facts presented in expository texts. Evaluate the credibility of an author's argument or defense of a claim by critiquing the evidence.

3. Synthesize information from multiple sources and identify complexities and discrepancies in the information.
4. Present information purposefully and succinctly. Write research reports that pose relevant and tightly drawn questions about the topic.
5. Analyze an author's implicit and explicit assumptions and beliefs about the subject.
6. Clarify word meaning through definition and example. Analyze text that uses the cause-and-effect organizational pattern.
7. Critique the power, validity, and truthfulness of arguments set forth in public documents.

It will be noticed that there is a close correspondence between these standards and the elements of the scientific paradigm.

The Scientist's Way of Thinking

To perceive the depth of the connection between the standards for language arts and social studies and the elements of scientific thinking, it is necessary to look deeper into how various habits of mind are manifested in the work of scientists. This section examines those habits of mind: curiosity, creativity, objectivity, skepticism, and open-mindedness. The next section will look at the methods that scientists use: investigation, measurement, analysis, and understanding. Each discussion is followed by a short list of things that teachers can do to encourage that habit of mind in their class.

Curiosity

Curiosity is the spark of mental aliveness. It is the emotional force that moves a person to investigate something, to discover how things work. Like children, scientists are curious about unfamiliar and puzzling things. Their curiosity fuels a drive to understand deeply and, guided by intuition, propels their investigation of the mysteries of the natural world and the universe.

Scientists are fascinated by the unknown. Anthony van Leeuwenhoek spent years in the 16th century investigating the wondrous new forms of life he could see in his microscope. Marie and Pierre Curie were fascinated by the strange penetrating emanations from certain heavy metal salts discovered by Antoine Becquerel. The Curie's investigations led to their discovery of radioactivity.

Scientists express their curiosity in the form of questions. They habitually ask, "What? Why? How? What if?" For example, in the 19th century the central quest in chemistry was to understand the pattern in the relationships of the elements, for example, why sodium and potassium, or mercury and lead, have similar chemistries and why chemical properties repeat every eight atomic mass units. That quest culminated in the periodic table of the elements.

Scientists understand that there are no forbidden questions. Every fact, every theory, and any authority can be challenged. Carl Sagan wrote: "There are naive questions, tedious questions, ill-phrased questions, questions put after inadequate self-criticism. But every question is a cry to understand the world. There is no such thing as a dumb question" (1996, p. 322).

This driving curiosity is reflected in the third social studies standard, "Critical thinking requires a questioning mind," as well as in the first standard for language arts, "Ask and evaluate questions."

How might students express their curiosity? They do so with the questions they ask. A student in a history class might ask, "Why is democracy the best form of

government?" or "What would our country be like if the English had won the Revolutionary War?" A student in a language arts class might ask, "What's so great about Shakespeare?" or "Why do we bother with poetry?"

Lessons for Teachers

- Let the students absolutely know that there are no forbidden questions. Encourage them to ask "Why?" "How?" and "What if?" about their assignments and gently guide the inquiry.
- Ask the students what parts of a subject fascinate them and what they are curious about. Encourage them to express their curiosity as a question. Help them refine vague or broad questions into pointed questions and guide their inquiry for answers.
- Point out new knowledge in the subject that was prompted by someone's curiosity and persistent inquiry.

Creativity

Creativity is the force that drives scientists to develop explanations for new phenomena. It also enables them to create new measurement tools and new experimental techniques.

Albert Einstein said, "Imagination is more important than knowledge." He imagined how a beam of light would look to someone riding on it, and this led to the Special Theory of Relativity.

Imagination, intuition, aesthetic sense, and logic guide scientists' work. They often use mental models to

develop a theory that can explain a new phenomenon. For example, Max Planck used a set of gears as a model for his thinking about electromagnetic forces.

Scientists are willing to speculate about the nature of things and to offer radical hypotheses. In the 19th century van't Hoff and Bel enabled chemistry to leap forward when they postulated that the four valence bonds of carbon are tetrahedrally oriented.

When scientists make their speculations and hypotheses public, they must have the courage to risk failure or ridicule. For example, in 1912 Alfred Wegener proposed a hypothesis about the movement of continents, and it was ridiculed during his lifetime. His idea was later vindicated, and it is called Plate Tectonics.

Scientists frequently challenge common assumptions; and when a false assumption is discredited, it provides space for creative new ideas. For example, chemists in the 19th and early 20th centuries assumed that the dark tarry residue in the bottom of reaction flasks was useless. Then someone looked closer and found the first examples of synthetic polymers; thereafter, chemists began making synthetic polymers, such as Nylon. When scientists questioned the unstated assumption that superconductors must be metallic, they quickly discovered a better class of superconductors made of ceramic material.

Silvano Arieti (1976) wrote about the conditions necessary to foster individual creativity. He said that it requires time to be alone, not being afraid to daydream, allowing the mind to wander in any direction without restraints, always being ready to catch the similarities

between different and apparently irrelevant elements, being willing to explore everything before rejecting anything, and being alert and disciplined to recognize the order in particular similarities for which there was no previous awareness. His prescription can be strongly endorsed by scientists, artists, and, indeed, by everyone who is trying to do creative work.

The need for creativity is expressed in the third standard for the language arts: "Synthesize information from multiple sources."

Students can express their creativity by articulating their imagination and by speculating about causes and outcomes. In social studies, students could speculate on how our culture has been influenced by Chinese immigration.

Lessons for Teachers

- Mention new techniques and theories in the classroom subject and tell how they were created.
- Require students to search a chapter in their textbook (selected by the teacher) for any assumptions, and question whether those assumptions are correct.
- Choose something in the textbook that is not explained and then require the students to offer an explanation. Discuss the various speculations to show how they can contribute to a better explanation.
- Have teams of students consider a lesson topic from a fresh perspective — for example, as if they were from a different culture or in a different profession — and see how it changes the interpretation.

Objectivity

All humans have biases that tend to color our thoughts. Objectivity is an essential balance to this inherent human subjectivity. For this reason, scientific investigations deal with actual objects, conditions, or phenomena. Scientific records and reports must express facts or conditions as measured or observed without distortion by personal feelings or prejudices. The data and results that deviate from a scientist's preconceptions must be recorded and evaluated, rather than discarded or glossed over. And other scientists withhold acceptance of new observations until those observations have been confirmed by others.

Another dimension of objectivity is rigorous intellectual honesty. Beyond the accurate reporting of experimental results, this means that scientists acknowledge their doubts about their results or interpretations. A habit of honesty makes it easier to perceive what is still unknown.

The need for objectivity is expressed quite clearly in the standards for history and social studies. The second standard for the social studies says, "Through the study of controversial issues, students should learn that judgments should be based on reasonable evidence and not on bias and emotion." The fourth standard says, "A most basic study skill of the history-social science fields involves. . . reaching reasoned conclusions based on evidence, and developing sound judgment." And the fifth standard says, "Students develop the ability to . . . distinguish among facts, opinion, and reasonable judgment."

Students might express their objectivity by inquiring about the facts in an issue and considering how they may be distorted by bias. In history students could compare the "facts" of an event as reported in their textbook with those reported in encyclopedias or other history books. In language arts they could discuss the latent facts and heavy coloration in advertisements aimed at teenagers.

Lessons for Teachers

- Strive for students to experience the subject as directly as possible.
- Help students understand how ever-present subjective factors, such as desire and dislike, can obstruct or distort knowing and understanding. Use contemporary examples.
- Discuss the kinds of "flags" that would incline a person to accept or reject facts or explanations. Illustrate with contemporary examples.
- Using published articles on a controversial current topic, identify and discuss facts, purported facts, biased opinion, doubts, and what is missing.
- Have students criticize weak evidence in textbook sections selected by the teacher.

Skepticism

Skepticism is an essential mental filter. However, teachers need to be clear that skepticism does not mean cynicism. It means the doctrine that because true knowledge is uncertain, we should exercise suspended judg-

ment, systematic doubt, and criticism. Any unsupported fact, cherished theory, or pronouncement by an authority can be questioned.

The Committee on Science, Engineering and Public Policy, a joint committee of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine, put it this way: "The fallibility of methods is a valuable reminder of the importance of skepticism in science. Scientific knowledge and scientific methods, whether old or new, must be continually scrutinized for possible errors" (1995).

In science, skepticism represents a finely honed ability to intuitively scan new information or explanations to see if they are congruent with existing information or theories. It does not lead to rejection of the information or explanation, but it raises a flag that says, "Caution!" According to Carl Sagan, "What skeptical thinking boils down to is the means to recognize a fallacious or fraudulent argument" (1996, p. 210).

Scientists often express doubts about questionable new facts and theories, for example, cold fusion, quantum mechanics, and plate tectonics. That does not mean that they always are right, or even that false ideas are not accepted. For example, Piltdown Man, a famous hoax in anthropology, was made possible by a failure of skepticism.

The need for skepticism is stated quite plainly in the third standard for history and social studies: "Critical thinking requires a questioning mind and a skeptical withholding of assent about the truth of a statement until it can be critically evaluated."

How might students express their skepticism? They do so every time they question the truth of a television commercial and even when they question the value of learning a subject in school. In history they might discuss the public's skepticism about official reports on the progress of the Vietnam or Persian Gulf wars. In language arts they could question the value of reading old novels.

Lessons for Teachers

- Encourage students to question unsupported assertions of fact or unconvincing explanations in their textbook. Point out chapters that contain such weaknesses.
- Discuss the kinds of "flags" that can alert a person to be skeptical about the content of an article they have read or a speech they have heard.
- Point out formerly accepted wisdom in the class subject that has been rejected.
- Challenge conventional ideas, such as "the poor will always be with us" or "more roads will alleviate traffic congestion."

Open-Mindedness

An open mind is an antidote to a universal infatuation with one's own ideas. It is invaluable in searching for the best ideas, regardless of their sources. An open mind also balances a skeptical attitude. Even though skeptical of reported "cold fusion," several reputable scientists kept an open mind. They read the reported

evidence, listened to supportive arguments, and made their own investigations.

Science is a communal activity that demands consensus. Results are not established as facts and explanations are not established as theories until there is consensus among the scientists who practice in that area. Controversy is not avoided; it is embraced as a challenge for better facts and stronger theories. New ideas and experimental results are presented and vigorously debated at numerous conferences, usually with open minds. After several independent investigations of cold fusion and vigorous debates of the results, cold fusion did not withstand the test of consensus.

The need to keep an open mind is part of the second standard for history and social studies: "Teachers present controversial issues honestly and accurately within their historical or contemporary context."

How might students express an open mind? They do so when they debate a proposition and try to decide which argument is better and when they consider ideas that are different from those they believe.

Lessons for Teachers

- Encourage students to notice information or ideas in the textbook that conflict with what they believe. Ask them, "What do you find it hard or impossible to believe?" Then help them impartially examine the idea or information from different viewpoints.
- Take a contentious current topic, such as global warming or fluoridation of water; divide the class into opinion groups; and have them argue about it

without getting personal. Afterward, ask them what they learned from the other group.

Scientific Methods

In addition to fostering certain habits of mind, scientists also use particular methods to examine their subjects. While it would be inappropriate to use an electron microscope to try to explain a poem, there are some general scientific methods that will help students understand almost any subject. This section looks at those methods, including investigation and measurement, analysis, and understanding.

Investigation and Measurement

These two topics are discussed together because investigation requires suitable measurement and observation tools.

Investigation is about planning, doing, and reporting incisive interactions with nature. It is the vehicle for purposeful discovery. Scientists use two basic methods for investigating something: experimentation and directed observation.

Scientists carefully select what to investigate and pose cogent questions. For example: How do the timing and strength of a spark affect the efficiency of an automobile

engine? How do the size and magnitude of the ozone hole over Antarctica vary with the seasons? Scientists then suggest possible answers to those questions and carefully plan and conduct experiments to test those answers. Planning is guided by applicable theory and by prior related work.

That does not mean that chance or accident play no role in scientific discovery. One famous example is the discovery of penicillin by Fleming, who noted that some of his bacterial cultures were not growing as well as they should have. However, such serendipity leads to useful discoveries only through the sagacity of the observer. As Pasteur said, "In the fields of observation, chance favors only the prepared mind."

An important part of a scientific observation is measurement. Measurement techniques extend our senses and provide quantitative data that can be used to analyze phenomena and test hypotheses.

Examples of measuring devices are rulers, scales, clocks, microscopes, and Geiger counters. When existing measurement techniques are inadequate to obtain accurate information, scientists may invent a new method; and they always evaluate the accuracy and reliability of each new method. Scientists frequently adapt existing methods for other uses; for example, nuclear magnetic resonance was developed in physics, used in chemistry to study molecular structures, and then used in medicine for imaging organs.

Investigation and measurement are explicitly mentioned in the fourth standard for history and the social studies, "the most basic skills of the history-social

science fields involve obtaining information and judging its value," and in the first standard for language arts, "Ask and evaluate questions, and develop ideas leading to inquiry, investigation, and research."

Students often are required to do investigations, whether it is examining the differences in writing styles between newspapers, novels, and letters or looking for evidence that something occurred in history. What often is missing from these investigations is a statement of the question they wish to answer and careful measurements to provide good information.

In language arts, students can discuss several techniques used by journalists to obtain accurate and reliable information. In history they can investigate how and why the industrial revolution started in England. And in social studies they might investigate a recent environmental issue in their community or state.

Lessons for Teachers

- Create teams of students to propose how they can get information about a topic in which some of them have expressed curiosity.
- Begin with a pointed question. Show students how a question that produces a qualitative answer often can be replaced by a question that yields a quantitative answer.
- Plan an investigation by first considering the amount and quality of information required to achieve the purpose of the investigation, and then consider what measuring and recording techniques can provide that information.

- Where possible, select a subject that can be manipulated and have the students conduct a controlled experiment. Where that is not possible, decide under what conditions observations can be made with the least contamination by uncontrolled events and human bias.
- Follow standards of investigation: record all information without altering or slanting to make it conform to one's preconceptions; take precautions to minimize the effects of human bias (for example, by using blind experiments or several groups of investigators); and especially note surprising results.
- Practice accepted standards when reporting results of the investigation. Reports should contain a statement of purpose, a description of investigative conditions, how results were measured, what conclusions were reached, comparison with prior investigations, and what future investigations are indicated.

Analysis

Analysis consists primarily of evaluating the validity of new information and arranging it for easier interpretation. Analysis transforms raw data into valid and useful information. It judges the quality of information and, therefore, the level of confidence in conclusions derived from it.

Scientists use symbols, figures, and mathematics to describe their work. Raw data are often recast as graphic representations and algebraic equations. Wherever

possible, qualitative statements are converted into quantitative statements.

Analysis also includes a search for unstated assumptions and personal bias. With complex phenomena, it often is useful to distinguish between types of causes. For example, sufficient causes are the most powerful; necessary but insufficient causes are next in potency; contributing causes are the least potent.

The ability to perform analyses is an important part of the current standards for education. For example, the third standard for history and social studies says that "Critical thinking requires . . . withholding assent about the truth of a statement until it can be critically evaluated." The fifth standard requires that "Students develop the ability to . . . identify unstated assumptions . . . and understand and distinguish cause, effect, sequence, and correlation." The second standard for language arts requires students to "Verify and clarify facts presented in texts. Evaluate the credibility of an author's argument or defense of a claim by critiquing the evidence." Other language arts standards require students to "identify complexities and discrepancies in the information" (third standard), "Analyze an author's assumptions and beliefs about the subject" (fifth standard), "Analyze text that uses the cause-and-effect organizational pattern" (sixth standard), and "Critique the power, validity, and truthfulness of arguments set forth in public documents" (seventh standard).

Students are using the skills of analysis when they can spot sources of error and bias, when they can recognize patterns or trends in data, when they point out

that other investigators have reached different conclusions, and when they recognize uncertainties in data or conclusions. In history classes, students might analyze the causes of an important event, such as women's suffrage laws. In social studies they could analyze the different assumptions behind minimum wage laws. And in language arts they could analyze how language is used by journalists to tell a story and to guide the reader to the reporter's conclusions.

Lessons for Teachers

- Use graphics with numerical information to estimate rates and the size of future effects. Notice if the relationship between the variables is linear, logarithmic, exponential, asymptotic, etc.
- Look for relationships between causes and distinguish between sufficient, necessary, and contributory causes.
- Scrutinize published reports for unstated assumptions that may underlie the premise of the work or the interpretation of the results.
- Look for a pattern in numerical data and speculate about what it might mean. Consider underlying causes.
- When completing an analysis, explicitly indicate which issues are still unknown and which are uncertain.

Understanding

Understanding means the ability to explain past results and predict new results. It is the ultimate goal of science.

In seeking to understand a new phenomenon or an incongruous fact, scientists commonly speculate with several explanations and then combine the best ideas into a *testable* hypothesis. Although scientists, like other people, usually seek confirmation for their hypotheses, the rigorous test is done by trying to disprove it. A hypothesis is tested by describing all necessary consequences, then investigating to see if each consequence is never refuted.

To develop explanations for a complex phenomenon (for example, flying), scientists usually break it down into smaller parts (lift, drag, turbulence, etc.), develop an understanding of the parts, then synthesize theories of the separate parts into a whole. Models also are used to simplify complex phenomena, for example, global cycles of carbon, nitrogen, and oxygen are modeled by diagrams with arrows between the sources and the sinks of the gases; thermodynamic processes are modeled by idealized cycles of work and heat exchange with the surroundings. Models can provide a conceptual framework for developing a coherent theory.

To minimize misunderstanding of concepts, scientists are careful to use words with precise, agreed-on definitions. For example, they distinguish mixtures and solutions, extensive and intensive variables, inertial and gravitational mass. The word *entropy* has a strict operational definition, in contrast with the innumerable ways it is used in nontechnical articles.

A theory is a logical construct of concepts that accounts for a range of natural phenomena and allows correct predictions of results outside the domain of data

that led to it. Theories embody the core knowledge of science. A theory relates behavior or properties to the most basic characteristics of the subject. The kinetic theory of gases describes the behavior of gases of any composition; the three laws of thermodynamics account for changes in energy and work in any system; and quantum mechanics accounts for virtually all phenomena associated with atoms and molecules.

The power of theories goes beyond understanding and prediction: once embedded, they shape our thinking. For example, the theory of natural selection and speciation shapes how anthropologists think about fossil evidence; thinking about disease has been strongly influenced by the bacterial theory of infection and the mutation theory of cancer. Theories of economics, marketing, and labor relations shape a CEO's thinking about business.

When offering a new explanation of a subject, the investigator must be careful to acknowledge his or her doubts and uncertainties. Richard Feynman said, "The scientist has a lot of experience with ignorance and doubt and uncertainty, and this experience is of great importance, I think. When a scientist doesn't know the answer to a problem, he is ignorant. When he has a hunch as to what the result is, he is uncertain. And when he is pretty darn sure of what the result is going to be, he is still in some doubt" (Feynman 1988, p. 245). For example, there still are doubts (that is, different opinions) about the best interpretation of the theory of evolution; there is uncertainty about the reality of prions as infectious agents; and the nature of the huge mass of

dark matter in the universe is absolutely unknown (though there are several hypotheses). Clarity about an uncertain explanation is a potent force for a new investigation and better understanding.

Reports of scientific results are highly important because new observations do not become facts and new ideas do not become laws or theories until they are corroborated by the scientific community. At technical conferences, scientists must be able to make convincing oral presentations and defend their ideas and results to their colleagues. A report must do more than describe the present work; it also must acknowledge prior studies and describe how they are consistent with or differ from the present study.

Just as understanding is the ultimate goal in science, it is also the ultimate goal in education. This is reflected in the standards for social studies and language arts. For example, the fifth standard for history and the social studies emphasizes that "Students develop the ability to: formulate appropriate questions leading to a deeper and clearer understanding of an issue . . . and predict probable consequences of an event." The third standard for the language arts requires students to "Synthesize information from multiple sources, and identify complexities and discrepancies in the information." And the fourth standard requires them to "Present information purposefully and succinctly. Write research reports that pose relevant and tightly drawn questions about the topic."

Students express their attempts to understand when they offer a carefully thought-out hypothesis to explain something, when they apply an accepted theory to new

events, and when they try to predict what will happen in a hypothetical situation. In social studies students could discuss how Maslow's "Hierarchy of Needs" theory explains much behavior among students, teachers, and parents. In language arts they could develop a simple model of persuasive communication by discussing how they get other boys and girls to do what they want them to do.

Lessons for Teachers

- Model a complex topic and identify what are believed to be the most important factors affecting the properties or behavior.
- Speculate about possible causes of a phenomenon or behavior in the class subject, and use these speculations to create a hypothesis that can be tested.
- In a body of information about a subject, formulate a simple statement that accounts for much of the information. Notice what it does not explain.
- Examine new information about a classroom subject (for example, reports in newspapers or magazines) to see if it is consistent with what is described in the textbook. If it is inconsistent, consider which information is more likely in error.
- Take a textbook explanation that seems superficial or unconvincing and ask questions about it: Why does it seem to be a weak explanation? How well does it explain a related subject? Then try to express a better explanation.
- Identify a prevalent theory in the classroom subject and discuss what information led to it, how broad

a subject it covers, and what kind of explanations it offers. If the subject is controversial, discuss competing theories.

- Take an issue that intrigues students and lead a process of sequential questioning in order to gain a deeper understanding.

Conclusion

The methods of science and the mental habits of scientists can be applied usefully to many areas of secondary education. These lessons from science provide teachers with another technique to help their students develop valuable attitudes and thinking skills. They also will help students score better on state assessment tests.

But there are other reasons these skills should be fostered throughout the curriculum. After graduation, most students will work in business, government, health services, or education, where their ability to think, investigate, and create will be essential to their success. The methods and habits of mind associated with science — as well as knowledge of the facts of science — will be highly useful in all these roles. Michael Schulhof, a physicist and former CEO of Sony USA, spoke about the relevance of scientific thinking in business: "My experience has convinced me that a background in pure science is an ideal preparation for business. The lessons I learned as a scientist were excellent instruction for business" (Schulhof 1992, p. 138).

The value of these skills goes beyond just being a productive worker. In the "Internet Age," we are flooded

with information, often of poor quality. One day each of our students will need to make decisions about such complex issues as taxes, elections, health care, stock investing, and loan financing. They will need to know how to gather information, how to evaluate its value, and how to analyze it. The mental skills of science will be valuable for everyone who must deal successfully with life's challenges.

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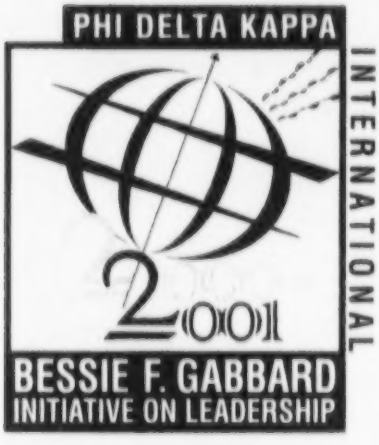

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The Bessie F. Gabbard Initiative on Leadership in Education for the 21st Century, dubbed the 2000-2001 Celebration for short, reaffirms the central importance of the Phi Delta Kappa tenet of leadership. Bessie F. Gabbard, the "First Lady" of PDK and a member and longtime chair of the board of governors of the Phi Delta Kappa Educational Foundation, provided the impetus for this initiative, which will focus the energies of PDK members and staff during the two years of transition to the new millennium. During this 2000-2001 Celebration, special attention will be paid to leaders and leadership in education with a particular focus on PDK's traditional advocacy on behalf of the public schools.

ISBN 0-87367-672-6

Hands-on science asks kindergartners to identify items that can be picked up by a magnet in this photo, circa 1953.

Courtesy of the Cleveland Public Library Photograph Collection.